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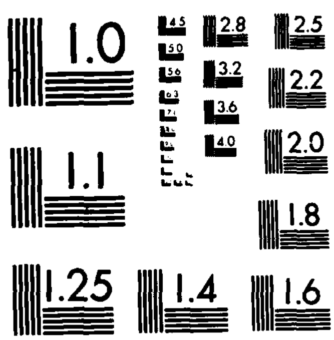
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AN INVESTIGATION OF CHANGES IN
DIRECT LABOR REQUIREMENTS
RESULTING FROM CHANGES IN A-10
AIRCRAFT PRODUCTION RATE

Philip E. Bourgoine, Jr., Captain, USAF
Kathy R. Collins, Captain, USAF

LSSR 35-82

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The addition of the production rate variable to the standard learning curve model has been studied extensively, and has been validated for use in estimating direct labor requirements for airframes, avionics equipment, aircraft engines, and missiles. This research set out to determine if the production rate model is valid for modern aircraft production using data obtained from the A-10 aircraft program. The results of the research indicated that the model was not useful for A-10 direct labor hour estimating. It was concluded that the reasons for the model's failure were due to a high correlation between the independent variables (cumulative output and production rate). In addition, most of the variation in direct labor hours could be attributed to the learning curve and not to the production rate because the data was obtained from the early stages of the learning curve. This research discussed the type of program which may be applicable to the production rate model.

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AN INVESTIGATION OF CHANGES IN DIRECT LABOR REQUIREMENTS RESULTING FROM CHANGES IN A-10 AIRCRAFT PRODUCTION RATE

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

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CHAPTER I

INTRODUCTION AND OVERVIEW

"Public money ought to be touched with the most scrupulous conscientiousness of honor [21:p.3-2]." The Department of Defense (DOD) operates with budgeted monies provided from the taxes of American citizens. In an era of limited resources, the Department of Defense is under ever-increasing pressure from Congress and the American public to provide national security at the lowest feasible cost (21:p.3-1).

Weapon systems acquisition has become increasingly complex and costly in the last decade. Budgetary and resource constraints coupled with rapid technological advances have mandated the need for more accurate cost-estimating techniques. Increased attention in this area is necessary to avoid such problems as cost overruns and project delays. In essence, every decision to expend public resources should be a cost-effective one (21:p.3-1).

Cost-effective decisions can be rendered if more specific cost determinants are identified. Past experience indicates that direct labor requirements are a significant determinant of cost. This is exemplified by the concurrent rise in labor costs and weapon system costs in the 60s, 70s, and 80s (21:p.3-1). Since variations in direct labor hours effect labor costs and subsequent total system costs, this research focused on direct labor hour components. Specifically, the effect of production rate on direct labor hour requirements was analyzed.

Background and Assumptions

The learning curve model is one method used extensively by the DOD to estimate direct labor requirements in production (10:465). The learning curve measures the amount of learning or experience gained in the production of some item (15:175). In simple terms, for every doubled number of production units a constant percentage of labor hours can be decreased due to learning; consequently, unit production costs are reduced (7:1). Standard learning curve theory is based upon the following assumptions:

1. The production item should be sizable and complex and should require a large amount of direct labor.
2. The majority of assembly operations should not be mechanized or machine-paced.
3. Learning curves applied from past experience should be adjusted for any differences in items, process, or other aspects of production.
4. The production process should be a continuous one and the item and product changes kept to a minimum.
5. Historical data should be available to compute the curve, since estimated data have low reliability.
6. There should be no external production rate changes [6:2].

The apparent limitation of the last assumption (no external production rate changes) has been the subject of considerable research since production rate changes may have predictable effects on total system costs (2:4; 7:1).

The focus of previous research has been to alter the learning curve model so that production rate variability can be incorporated. These previous studies are discussed in Chapter II.

In one study, Larry L. Smith (19) developed a cumulative production and production rate model which indicates possible effects of production rate changes on unit costs. Further replications of Smith's research effort are necessary to substantiate the value of his model for more effective unit cost estimates.

Problem Statement

Addition of the production rate variable to the standard learning model could lead to fewer labor costs in current production programs. The effect of changes in the production rate on direct labor requirements for A-10 fighter production is not known. The results of this study could lead to future cost reductions in the ongoing A-10 program.

Research Objectives

The primary objectives of this research were: (1) to identify the impact on direct labor requirements resulting from production rate changes in the A-10 fighter program, and (2) to further validate the aptness of Smith's cumulative production and production rate cost model.

Research Hypotheses

The hypotheses tested in this research were: (1) production rate variability explains a significant amount of the variation in direct labor requirements for A-10 production, and (2) Smith's production rate model is a better predictor of direct labor requirements than the standard learning curve model.

Justification, Scope, and Limitations

As stated in the introduction, there has been a dramatic rise in direct labor costs since the early 60s. These labor costs coupled with the increasing complexity of modern weapon systems have increased the difficulty of accurate cost estimation. Because inaccurate cost estimates for modern complex weapon systems can result in program delays and cost overruns, it is necessary to investigate methods available for more accurate cost estimation.

The scope of this research was to investigate the applicability of a cost estimation method, Smith's cumulative production and production rate model, to a modern weapon system program.

This research effort was limited to investigating the usefulness of the cumulative production and production rate model for the A-10 fighter aircraft program. Since the A-10 is an ongoing program, the results of this study may be of value for future negotiations on this program.

Summary

The learning curve model has been used extensively to estimate direct labor requirements for production programs. Several researchers have attempted to improve the accuracy of cost estimation by evaluating the effects of production rate variability on labor requirements and system costs. This research effort evaluated the value of adding the production rate variable to enhance the prediction of direct labor requirements for the ongoing A-10 aircraft program.

The problem, objectives, and hypotheses were stated in this introductory chapter. Chapter II contains the theory of the basic learning curve and a synopsis of past research in this area. The research hypotheses and the methodology for testing these hypotheses are the topics of Chapter III. Chapter IV discusses the data analysis and evaluation. Chapter V contains the summary, conclusions, and recommendations for further research effort.

CHAPTER II

LITERATURE REVIEW

> The learning curve has been used extensively in the aircraft industry during the last thirty years to assist in cost estimating for major DOD weapons acquisition programs. Since the introduction of the basic learning curve model, a number of variations have been developed in an attempt to achieve a greater accuracy in predicting actual cost figures [6:6].

This chapter traces the development of learning curve cost estimating techniques. It is limited to standard learning curve theory and subsequent research efforts in this area. Major emphasis was focused on the research effort of Larry L. Smith (19) since his model was used as the basis for this research.

Learning Curve Models

The two basic learning curve models are the cumulative average model[1] and the unit curve[2] model. In February 1936, T. P. Wright, generally regarded as the pioneer of learning curve theory, documented his cumulative average cost curve in an article entitled, "Factors Affecting the Cost of An Airplane" (22:122-128). This is regarded as one

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[1]The cumulative average model is also referred to as the Northrop variation.

[2]The unit curve model is also called the Boeing variation.

of the earliest efforts toward mathematically modeling learning curve theory for aircraft manufacturing.

The mathematical form of Wright's model (3:16-17) was:

$$\overline{Y} = AX^B,$$

where,

$\overline{Y}$ = the cumulative average direct man-hours,

A = the number of direct man-hours to build the first airframe,

X = the cumulative number of airframes produced, and

B = the slope parameter (a function of the improvement rate).

Following World War II, a U.S. Government-sponsored study at Stanford Research Institute validated the unit curve model. Two hundred jobs in the airframe manufacturing process were studied. From this airframe production data, J. R. Crawford (5:8) concluded that direct labor hours should be represented by the model, $Y = AX^B$. All variables in Crawford's model were the same as the Wright model with the exception of Y. In Crawford's model,[3] Y represents the direct labor hours for the Xth unit (not a cumulative average).

---

[3]This variation, which evolved from unit curve theory (Boeing theory), will be referred to as the standard model for the remainder of this thesis.

Both Wright's and Crawford's standard learning curve models are limited by not accounting for external production rate changes. This limitation has led to much concern due to the following factors:

> . . . (1) workers will adjust according to pressure to speed up or slow down production; (2) as more workers are employed, the distribution of tasks to each individual worker should narrow; and (3) at higher production rates, tooling costs can be widely allocated to larger numbers of units [20:44].

Labor Requirements Prediction Models: Addition of the Production Rate Variable

The concerns listed above resulted in numerous studies which addressed production rate effect on direct labor requirements (1; 2; 3; 4; 5; 6; 8; 11; 14; 18; 19; 20). This section contains a synopsis of the findings and conclusions of these studies.

Asher

One of the earliest studies in the area of production rate effect on direct labor was conducted by Asher (3:87) who subjectively evaluated the effect of production rate changes on direct labor hour requirements using empirical data from several airframe production programs.

> Asher noted that there are two ways that the rate of production could influence unit labor cost. It could affect the machine set-up time, that is the number of hours charged to each unit of production. And it could, according to Asher, affect the number of subassemblies in a manufacturing process which in turn, could lead to an effect on the number of hours of subassembly work charged to a unit [20:21-22].

Asher concluded that production rate changes were not very significant compared to cumulative production effects. With the exception of set-up time and subassemblies, he believed there would be little difference in unit hours per month regardless of the quantity of units produced. However, other researchers believed that production costs were dependent on several factors, including production rate.

<u>Alchian and Allen</u>

Alchian and Allen (19:19) believed that production costs were dependent on (1) the volume produced, (2) the production rate, and (3) the time span between the decision to produce and actual production. Alchian and Allen's study produced three major conclusions.

> First, larger total volumes lead to smaller unit costs because of increased product standardization that accompanies larger volume. Second, unit costs increase with increasing production rates because more overtime and less efficient workers are needed to support the increased production rate. Third, the cost variable increases if the initial production start-up time is compressed [2:9-10].

Alchian and Allen did not empirically test their conclusions; however, their ideas may be applicable to the airframe industry (19:20).

<u>Colasuonno</u>

In 1967, V. Colasuonno (4:66-75) analyzed the conceptual advances and uses of learning curve theory. Five of the seven airframe manufacturers contacted subjectively evaluated the cumulative production and production rate model in addition to using the learning curve model. He concluded that better cost estimates would be rendered if all factors affecting cost estimates were categorized and considered in a more systematic manner.

Johnson

The first researcher to empirically show the significance of production rate variability was Gordon J. Johnson (12) who concluded that production rate was a significant factor in predicting unit cost. He applied the additive model shown below to four sets of rocket motor data (12:30).

$$Y = A + BX_1 + CX_2^Z$$

where,

Y = direct labor hours per month,

X_1 = production rate in equivalent units per month,

X_2 = cumulative units produced as of the end of each month, and

A, B, C, Z = model parameters.

Study results showed that inclusion of the production rate variable resulted in more accurate estimates of the direct labor hours per month. This is denoted by the increased coefficient of determination[4] (R^2) in Table 1. Johnson attributed the poor results of data set 3 to an inadequate accounting system used by the manufacturer (12:37). Johnson's efforts were further validated by Ilderton.

TABLE 1

SUMMARY OF JOHNSON'S ANALYSIS (12:34)

	R^2 for Data Set #			
Regression Variables	1	2	3	4
Labor Hours vs Cumulative Units	.753	.395	.00678	.763
Labor Hours vs Cumulative Units and Production Rate	.932	.808	.308	.927

Ilderton

Ilderton analyzed computer programs that were written to fit learning curves to production data. He recommended more factors be included in the standard learning curve model. Production rate variability was the first factor suggested by Ilderton for inclusion in the basic model (11:69-71). The research methods of Ilderton and Johnson were first applied to airframe data by Orsini.

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[4]The coefficient of determination (R^2) is a sample statistic that indicates how well the model fits the data. $R^2 = 0$ implies a complete lack of fit of the model to the data while $R^2 = 1$ implies a perfect fit (14:350).

Orsini

Orsini (18:57-80) applied Johnson's rocket motor model (see Table 2) to C-141A airframe data. He regressed the data using the standard unit learning curve model followed by regression using Johnson's additive model. He also regressed the data after converting Johnson's additive model into the multiplicative model,

$$Y = e^{B_0} \cdot X_1^{B_1} \cdot X_2^{B_2}$$

where,

Y = direct labor hours per quarter,

X_1 = number of units produced per quarter,

X_2 = cumulative number of units produced as of the end of each quarter,

B_0, B_1, B_2 = model parameters, and

e = the base of natural logarithms (2:11-12).

The results of Orsini's regression analysis are summarized in Table 2.

> Orsini drew three major conclusions from his studies. First, the production rate variable contributed importantly to the explanatory power of both the additive and multiplicative models. Second, the multiplicative model was a better predictor than the additive model because the estimate of the Z value was eliminated. Third, Orsini indicated that inclusion of the production rate in the learning curve model yielded more accurate results and would possibly lead to significant revisions and improvement of cost estimating [20:15].

Large, Hoffmayer and Kontrovich, who also examined airframe data, believed that specific production changes were equally or more important than rate changes.

TABLE 2

SUMMARY OF ORSINI'S REGRESSION ANALYSIS (18:68-69)

Model	Z Value/Slope*	R^2
Without production rate variable		
$Y = B_0 + B_2X_2^Z$	- .3219/80	.695
	- .4529/73	.600
$Y = e^{B_0} \cdot X_2^{B_2}$	-1.3219/40	.253
	--	.883
With production rate variable		
$Y = B_0 + B_1X_1 + B_2X_2^Z$	- .3219/80	.910
	- .4529/73	.907
$Y = e^{B_0} \cdot X_1^{B_1} \cdot X_2^{B_2}$	-1.3219/40	.882
	--	.955

*The slope of the learning curve equals 100 minus the rate of learning. The rate of learning is the constant percentage decrease in hours to produce per unit as the total quantity of units produced doubles. The Z value is the model parameter obtained from application of Johnson's model (18:70-71).

Large, Hoffmayer and Kontrovich

During a study sponsored by the Office of the Secretary of Defense, Large, Hoffmayer and Kontrovich (13:46-60) examined airframe data in attempting to develop a general cost estimate model. According to Smith (19:30), their model was of the form,[5]

$$Y_i = A \cdot W^B \cdot S^C \cdot R^D$$

where,

Y_i = the cumulative direct manufacturing labor hours through unit i,

W = the program average weight in pounds as expressed by the Defense Contractor Planning Report,

S = the maximum design airspeed in knots,

R = the production rate expressed as the time in months for acceptance of the first i airframes (Large et al. chose i arbitrarily to be 100 or 200), and

A,B,C,D = model parameters.

Of the four labor hour factors examined (manufacturing labor, manufacturing materials, tooling, and engineering), they concluded that production rate effects could not be predicted with confidence (13:41). The authors stated that each case should be examined separately to determine the specific manner in which production changes occurred (13:50-51). Large et al. felt that specific production

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[5]The mathematical form of the model was not included in the original source.

changes were as much or more important than the size of the rate change.

However, Smith (19:31) indicated that true effect of production rate changes was obscured in the Large et al. model due to the averaging effect that resulted from using the acceptance span (time in months from start of production of the first i airframes until final acceptance) as an indicator of production rate. Noah's research findings were contrary to Large et al.; however, they supported Orsini's conclusions.

Noah

Joseph Noah (2) analyzed A-7 and F-4 airframe cost data using a four-dimensional model of the form,

$$Y = e^{A} \cdot X_1^{B} \cdot X_2^{C} \cdot X_3^{D}$$

where,

Y = average direct labor hours per pound of airframe for each airframe lot,

e = the base of the natural logarithm,

X_1 = the cumulative volume in pounds of aircraft produced by the midpoint of each airframe lot,

X_2 = the production rate in average pounds of airframe delivered per month for the entire period,

X_3 = the annual volume of aircraft in airframe pounds, and

A,B,C,D = model parameters (2:13).

Using a log-transformation of the above model, Noah regressed the data and obtained R^2 values of .80 and .99 for the A-7 and F-4 data respectively. Noah's analysis revealed that the production rate variable was a significant determinant of the direct labor requirements (5:16).

In an attempt to formulate a generalized cost model, Noah averaged the regression coefficients (B, C, and D) obtained from the A-7 and F-4 data. Noah's attempt at a generalized model led to other work in this area, including a major effort by Smith who felt that additional aircraft programs needed to be applied to Noah's generalized model to determine if it was an accurate predictor of direct labor requirements.

<u>Smith</u>

In his doctoral dissertation, "An Investigation of Changes in Direct Labor Requirements Resulting from Changes in Airframe Production Rate," Smith formulated a generalized model in an effort to provide a more precise prediction of direct labor requirements for additional airframes in specific programs (19:3).

> Specifically, he [Smith] wanted to develop a single cost model form that could be tailored to any given program, but he did not consider a generalization of model coefficients between programs to be appropriate [5:17].

Smith chose a modified version of Orsini's multiplicative model in the form,

$$Y_i = B_0 \cdot X_{1i}^{B_1} \cdot X_{2i}^{B_2} \cdot 10^{e_i}$$

where,

Y_i = the unit average direct labor hours needed to output each pound of airframe in lot i,

X_{1i} = the cumulative learning accrued from experience on all airframes of the same type through lot i,

X_{2i} = the production rate of lot i for all airframes of the same type,

e_i = the variation of each dependent variable which is not explained by the two independent variables, and

B_0, B_1, B_2 = model parameters (19:43).

He chose this model because:

> Other writers had suggested that it might be a good predictor in this application. Multiple regression analysis is facilitated by this choice. Finally, investigation of some test data indicates that it works well [19:43].

The linearized form of the model used by Smith to facilitate multiple regression was

$$\text{Log } Y_i = \text{Log } B_0 + B_1 \text{ Log } X_{1i} + B_2 \text{ Log } X_{2i} + e_i$$

(19:45).

The two production rate proxies used were the lot average manufacturing rate and the lot delivery rate.

> The lot average manufacturing rate included the number of airframes in a lot divided by the lot time span, where lot time span was the time between release date from the lot for the first airframe in the lot. The lot delivery rate was the actual monthly airframe acceptance rate [2:14-15].

Smith regressed historical production data (F-4, KC-135, F-102) using his full model ($Y^i = B_0 \cdot X_{1i}^{B_1} \cdot X_{2i}^{B_2} \cdot 10^{e_i}$) as well as a reduced model which excluded the production rate variable ($Y_i = B_0 \cdot X_{1i}^{B_1} \cdot 10^{e_i}$). By comparing the statistical results, he was able to identify the production rate's contribution to the predictive ability of his model (5:19). Smith performed regression analysis on sixteen data groups as well as predictive ability tests for twelve of the data groups.

The predictive ability test procedure used by Smith was to:

1. omit a portion of historical data,

2. regress each model against the remaining data to obtain model coefficients,

3. predict new values using the coefficients obtained, and

4. compare the new predicted values with the actual historical values in the production data (9:56).

Smith considered the predictive ability to be useful if the predicted and observed value did not deviate by more than 5 percent (19:96).

He made the following conclusions based upon his test results:

1. Production rate was correlated negatively with unit labor hour requirements.

2. Lot average manufacturing rate gave better results as a proxy for production rate than did the delivery rate. However, both proxies contributed importantly to the full model's explanatory power.

3. The full model fit the data better than the reduced model, as evidenced by R^2 values.

4. The full model explained fabrication labor hour variations more fully than assembly labor hour variations.

5. The production rate variable stabilized and improved the predictive ability of the full model for the F-4 and F-102 programs, but tests for the KC-135 were either impractical for lack of sufficient data points or inclusive for the test situation containing sufficient data points.

6. Formulating a generalized cost model from results from the F-4, F-102, and KC-135 data would not be feasible since the model coefficients varied significantly (17:133-146).

Smith's regression analysis and predictive ability test results are summarized in Tables 3 and 4. Smith's research was replicated by numerous other researchers.

<u>Congleton and Kinton</u>

Congleton and Kinton replicated Smith's research efforts using T-38 and F-5 data. For selected F-5 and

TABLE 3

SUMMARY OF SMITH'S REGRESSION ANALYSIS (2:16)

Test Situation No.	Data Points	R_f^2** (actual)	R_r^2** (actual)	B_0	B_1	B_2
1	57	0.978	0.928	masked*	-0.261	-0.169
2	55	0.973	0.904	"	-0.246	-0.183
3	55	0.966	0.904	"	-0.257	-0.161
4	42	0.853	0.585	"	-0.230	-0.157
5	42	0.820	0.585	"	-0.229	-0.136
6	42	0.889	0.618	6.328	-0.221	-0.148
7	42	0.851	0.618	7.601	-0.219	-0.127
8	42	0.744	0.658	9.016	-0.279	-0.112
9	42	0.733	0.658	10.400	-0.278	-0.097
10	50	0.979	0.961	38.371	-0.299	-0.158
11	42	0.979	0.959	47.290	-0.344	-0.144
12	96	0.958	0.971	13.133	-0.453	-0.164
13***	7	0.974	0.903	0.674	-0.165	-0.305
14***	7	0.971	0.903	1.123	-0.233	-0.222
15***	7	0.994	0.964	13.338	-0.608	0.361
16***	7	0.992	0.964	7.303	-0.527	0.262

*The total production hours per pound were considered proprietary by the manufacturer, and these coefficients were masked in the published version of Smith's research (19:65).

**The subscripts for R^2 are as follows: f stands for full model; r for the reduced.

***Impractical for test situations.

TABLE 4

SUMMARY OF SMITH'S PREDICTIVE ABILITY TEST RESULTS (2:17)

Test Situation No.	Percentage Deviation*	
	Full Model	Reduced Model
1	-2.6	14.5
2	2.2	13.6
3	Not Reported	13.6
4	1.8	5.3
5	3.1	5.3
6	-7.8	Not Reported
7	**	Not Reported
8	-0.7	1.1
9	-4.2	1.1
10	-1.1	5.6
11	3.5	Not Reported
12	2.2	-3.3
13-16	***	***

*These tests were conducted as described in Chapter IV of Smith's research (19:56). All percentages are rounded to nearest tenth.

**Smith reported the results were deviations greater than those for test situation 6, but did not report a value (19:96).

***Smith reported that predictive ability tests were impractical for situations 13 through 16 because observations were limited to seven (19:71-131).

T-38 airframe models, the labor hour categories (total, fabrication, and assembly) were examined using the manufacturing and delivery production rate proxies (5:90). The research hypotheses tested and models (full and reduced) used were identical to Smith's.

From their research efforts, Congleton and Kinton drew the following conclusions:

1. The negative B_2 coefficients in all tests supported Smith's finding that production rate increases resulted in required labor hours per pound decreases (negative correlation).

2. All test situation findings supported Smith's conclusion that both manufacturing and delivery production rate proxies were "significant explainers of labor hour variations for each airframe model as well as labor hour variations for all models combined [5:93]."

3. Tests Situations 1-5 supported Smith's conclusion that the full model fit the data better than the reduced model.

4. Based on the comparison of R^2 values derived from Congleton and Kinton's research, the full model explained assembly labor hours more fully than fabrication labor hour variations. This was contrary to Smith's fourth conclusion.

5. The predictive ability of the full model did not pass the 5 percent deviation criterion (5:95); however,

it was substantially better than the reduced model's ability in eighteen of thirty data sets tested.

6. Smith's conclusion that ". . . coefficients should not be averaged between or even within production programs . . . [5:96]" was supported by Congleton and Kinton's finding that ". . . the regression coefficients often changed substantially within a given test situation as successive cases were omitted from the regressed data [5:96]."

Congleton and Kinton's findings largely reaffirmed and validated Smith's findings.

Dreyfuss and Large

In March 1978, Dreyfuss and Large studied the effect of extended low-rate airframe production on costs using the same data as Smith. "Dreyfuss and Large stated that very low rates of early output resulted in additional costs and that subsequent higher production rates resulted in cost benefits [6:22]." These findings, similar to Smith's conclusions, disproved Large, Hoffmayer, and Kontrovich's earlier findings that production rate efforts could not be predicted with confidence (6:22).

Stevens and Thomerson

Stevens and Thomerson's effort was the first attempt to apply Smith's model to data other than airframes.

They analyzed Magnavox ARC-164 radio and Teledyne Computer Signal Data Converter data. The authors' analysis "revealed that production rate was an important explainer of variation in direct labor hours for nine of the ten models evaluated [20:94]." "The predictive ability of the full model [which incorporated production rate] was better than that of the reduced model for eighteen months into the future [2:18]." Table 5 contains the coefficient of determination (R^2) values for the full and reduced models analyzed.

Additional conclusions by Stevens and Thomerson are as follows:

1. This research found that the production rate, when included in an appropriate model, stabilized the predictions over an extended interval.

2. Generalizing to other programs cannot work since, even for the same program, month-to-month sensitivity can be large.

3. Since the model can be tailored to avionics data, it may be applicable to other diverse programs (20: 102-104).

Further validation of Smith's model was done by Crozier and McGann, and Allen and Farr.

TABLE 5

SUMMARY OF STEVENS AND THOMERSON'S ANALYSIS (20:95)

Model	R^2 Reduced	R^2 Full
Magnavox 1	.480	.570
Magnavox 2	.816	.828
Magnavox 3	.482	.950
Magnavox 4	.816	.965
Magnavox 5	.022	.567
Teledyne 1	.073	.433
Teledyne 2	.955	.962
Teledyne 3	.073	.502
Teledyne 4	.955	.968
Teledyne 5	.235	.981

Crozier and McGann

Crozier and McGann applied Smith's reduced and full models to three aircraft engine programs (General Electric J-79, Allison TF-41, and Pratt and Whitney F-100).

> They found that the production rate significantly explained variation in direct labor hours in three of six cases examined, with especially good results on the F-100 engine. On all engine programs, the full model was a better predictor than the reduced model. Crozier and McGann concluded that the results when using Smith's model depend a great deal on the type of weapon system. This last finding justifies the need for more replication efforts of Smith's model [2:18-19].

Allen and Farr

Allen and Farr (2) also replicated Smith's research. They applied both the reduced and full models to Short Range Attack Missile and Maverick missile production programs. After applying Smith's methodology, Allen and Farr (2:100-103) formed the following conclusions: (1) production rate was a significant explainer of variation in direct labor hours in nine of twelve cases, (2) the usefulness of the full model versus the reduced model depends on the particular program and circumstances, (3) "Smith's model has widespread potential for missile production programs and merits additional study [2:101]," and (4) a general model cannot be developed that applies to all missile production due to coefficient sensitivity to program changes.

Summary

Numerous studies (1; 2; 3; 4; 5; 6; 8; 11; 12; 18; 19; 20) have been conducted in attempting to develop a model that will aid in more accurate predictions of direct labor requirements, a major determinant of per unit costs. The usefulness of adding a production rate variable to the standard learning curve model (used extensively by the DOD) has been addressed. Although there has been some dissension (3; 12), the majority of studies (1; 2; 4; 5; 6; 8; 18; 19; 20) concluded that production rate is a significant contributor to the predictive ability of the learning curve model. The basis for five such research efforts (2; 5; 6; 19; 20) has been the cumulative production and production rate cost model developed by Lt Col Larry L. Smith in 1975. All five research efforts indicated supporting results in at least parts of the selected programs studied. Table 6 summarizes the general areas that have been investigated.

This research effort attempted to answer the following questions:

1. Does production rate variability explain a significant amount of variation in direct labor requirements, and

2. Is Smith's production rate model a better predictor of direct labor requirements than the standard learning curve model?

TABLE 6

SUMMARY OF RESEARCH EFFORTS USING SMITH'S PRODUCTION RATE MODEL (2:102)

Area of Application	Researchers	Average R^2 Reduced	Average R^2 Full
Airframes	Smith	.818	.916
Airframes	Congleton/Kinton	.912	.953
Avionics	Stevens/Thomerson	.491	.773
Engines	Crozier/McGann	.402	.496
Missiles	Allen/Farr	.755	.805

Chapter III outlines the methodology used in this research effort.

CHAPTER III

RESEARCH METHODOLOGY

Introduction

Chapter I outlined the research problem, and Chapter II provided a review of the relevant literature that served as a foundation for the authors' research effort. This chapter provides the overall research methodology formulated to address the stated research problem. Chapter III is divided into seven major sections as follows:

1. Objectives and Approach
2. Model Definitions
3. Model Variables
4. Research Hypotheses
5. Data Collection and Treatment
6. Assumptions and Limitations
7. Summary

Objectives and Approach

Objectives

The primary objectives of this research were: (1) to identify the impact on direct labor requirements resulting from production rate changes in an ongoing production program, and (2) to further validate the aptness of Smith's cumulative production and production rate cost model.

Approach

The approach followed in this research project was to collect production data from the A-10 attack aircraft program and to evaluate the data using Smith's model (19) and the basic learning curve model as discussed in Chapter II. In all previous research using Smith's model for estimating aircraft cost, the aircraft used were no longer being produced. For this effort, the A-10 aircraft program was chosen because the A-10 program had historical data which could be used in this research, and it is an ongoing program. Thus, this research project may be of value in future Air Force cost negotiations for the A-10.

Model Definitions

The two models used by Smith (19:43) and tested in this research are repeated here for ease of reference.

The reduced model is the basic learning curve where:

$$Y_i = B_0 \cdot X_{1i}^{B_1} \cdot 10^{e_i}$$

In the full model the production rate variable is added as follows:

$$Y_i = B_0 \cdot X_{1i}^{B_1} \cdot X_{2i}^{B_2} \cdot 10^{e_i} .$$

The terms used in these models are as follows:

Y_i = direct labor hours,

X_{1i} = cumulative output,

X_{2i} = production rate,

e_i = the variation which is left unexplained by the variables in the model (residual),

B_0 = constant/intercept,

B_1 = regression coefficient associated with X_1, and

B_2 = regression coefficient associated with X_2.

The two models above were transformed to a linear form by taking the logarithm of each side of the equation. This logarithmic transformation was performed to facilitate multiple linear regression analysis. The logarithmic form of the reduced model is:

$$\text{Log } Y_i = \text{Log } B_0 + B_1 \text{ Log } X_{1i} + e_i .$$

The logarithmic form of the full model is:

$$\text{Log } Y_i = \text{Log } B_0 + B_1 \text{ Log } X_{1i} + B_2 \text{ Log } X_{2i} + e_i .$$

Both the full and reduced models have been defined. The model variables are described in the following section.

Model Variables

The three model variables included in this research project were:

1. direct labor hours,
2. cumulative output, and
3. production rate.

Each variable is briefly defined in this section. The data collection and treatment section contains a more complete description of the variables.

Direct Labor Hours Variable

Direct labor hours are measured in hours. The value used for the direct labor hour variable is the average monthly direct labor hours for an individual month during the period September 1977 through November 1981. This dependent variable pertains to all the direct labor hours expended for in-house production at Fairchild Republic's Farmingdale and Hagerstown plants.

Cumulative Output Variable

Cumulative output is measured in terms of the number of aircraft produced from the beginning of production until the end of a calendar month.

Production Rate Variable

The production rate is the number of aircraft produced during a calendar month. Since the research data did not include the production rate, the delivery rate is used as a proxy for the production rate. The use of a proxy is discussed further in the data collection and treatment section of this chapter.

The model variables have been described above. Prior to research hypotheses testing, scattergram analysis was performed to examine the data for learning curve conformity and inconsistencies.

Research Hypotheses

The two research hypotheses tested in this research project were:

1. The production rate variable explains a statistically significant portion of additional variation in direct labor hour requirements for A-10 aircraft production, and

2. The full model is a better predictor of direct labor requirements than the reduced model.

Research Hypothesis One

To test this research hypothesis, the transformed independent variables (cumulative output and production rate) were regressed with the transformed dependent variable (direct labor hours) to obtain the coefficients for the full model and its statistical parameters. The transformed independent variable (cumulative output) was regressed with the dependent variable (direct labor hours) to obtain the coefficients for the reduced model and its statistical parameters. The information obtained from these two linear regressions was used to perform two statistical and two criteria tests.

A statistical test is an objective test that enables a researcher to evaluate a research hypothesis at a predetermined risk of accepting a false hypothesis. A criterion test is a test of a research hypothesis by evaluating the properties and/or standards which are expected to those obtained from the research. These properties and standards are obtained from statistical assumptions or established by the researcher. A statistical test is more powerful than a criterion test since it uses accepted statistical procedures and a predetermined risk of error. A criterion test uses procedures and assumptions determined by the researcher, if no commonly accepted assumptions are available, and does not have the ability to determine the risk of accepting a false hypothesis.

A failure of any one of the four tests was sufficient to reject Research Hypothesis One. Therefore, the statistical tests were performed before the criterion tests since the statistical tests were considered more powerful than the criteria tests. The research tests in sequential order were:

1. Model utility test (statistical test),

2. Production rate variable value test (statistical test),

3. Model suitability (criterion test), and

4. Model appropriateness (criterion test).

These four research tests are described in subsequent sections.

Model Utility Test. The Model Utility Hypothesis stated that the cumulative output (X_1) and the production rate (X_2) variables were related to direct labor hours (Y). If X_1 and X_2 were completely unrelated to Y, Y would not change as X_1 and X_2 change. For the full model in this case, the coefficients, B_1 for X_1 and B_2 for X_2, were equal to zero. The null and alternate hypotheses were formulated as follows:

H_0: $B_1 = B_2 = 0$;

H_A: At least one of the coefficients is nonzero.

The null hypothesis was rejected if the F-ratio was greater than F-critical (4.17) at a significance level of 0.05. F-critical values were extracted from McClave and Benson's F-distribution tables (14:638-639).

For this first statistical test,

$$\text{F-ratio} = MSR/MSE$$

$$MSR = SSR/(p - 1)$$

$$MSE = SSE/(n - p)$$

where,

MSR = the mean of the sum of squares regression,

MSE = the mean of the sum of squares error,

SSR = the sum of squares regression,

SSE = the sum of squares error,

n = the number of data points, and

p = the number of model parameters (17:45,79, 227-228).

The F-ratio compares the variance explained by the regression model (MSR) to the unexplained variance (MSE) (17:45,79).

Production Rate Variable Value Test. If the null hypothesis of the model utility test was not rejected, the production rate variable value test was performed. This hypothesis tested the ability of the production rate variable to explain additional variance in direct labor hours per aircraft. The null hypothesis and its alternate were formed as follows:

$$H_0: \; B_2 = 0;$$

$$H_A: \; B_2 \neq 0.$$

As stated previously, the null hypothesis was rejected if the F-ratio was greater than the specified F-critical value (4.17) at $\alpha = 0.05$.

For this test,

$$\text{F-ratio} = \frac{\text{SSR(Full model)} - \text{SSR(Reduced model)}}{\frac{\text{SSE(Full model)}}{n-3}}$$

If the full model significantly explained more variance than the reduced model because of the inclusion of the production rate variable, the full model was considered better than the reduced model. However, even if the full model explained more variance due to multicollinearity, the production rate variable could be found to be an insignificant explainer of additional variance (17:252).

Because the production rate variable is a component of the cumulative output variable, it was assumed that varying degrees of multicollinearity exist. Multicollinearity exists when two or more independent variables contribute redundant information (14:418). Neter and Wasserman (17:249-259) discussed the effects of multicollinearity on regression coefficients:

1. The regression coefficient for a particular independent variable will change when the correlated independent variable is added to the model. Therefore, the new coefficient reflects only a marginal or partial effect due to its respective independent variable (17:252).

2. The sum of squares regression (SSR) cannot be ascribed to an independent variable as reflecting its

effect in reducing the total variation in the dependent variable. Thus, the other correlated independent variable must be considered since some of its contribution to explaining the dependent variables variation is already included in the first independent variable (17:253).

Due to the fact that Research Hypothesis One was that the production rate variable explains a statistically significant amount of additional variation in direct labor hours when the cumulative output is present in the model, the test would be considered valid even if multicollinearity is present. In support of this point, Neter and Wasserman state:

> The fact that some or all independent variables are correlated among themselves does not, in general, inhibit our ability to obtain a good fit nor does it tend to affect inferences about mean responses or predictions of new observations, provided these inferences are made within the region of observations [17:341].

Multicollinearity, with respect to the two independent variables, is discussed later in this chapter.

If the null hypothesis was not rejected, the residuals were analyzed to check model suitability.

Model Suitability Test. Using the observed data, residual analysis was employed to check the suitability of the full model (17:112). Residual analysis is a method of analyzing observed error terms (residuals) to ascertain if the residuals reflect the same properties which are assumed about the random error component (e). Specifically, the assumptions tested were:

1. Constant error term variance,
2. Normal error term distribution, and
3. Independence of error terms (17:239).

The model was appropriate if the observed residuals (errors) displayed the properties of constant variance, normal distribution, and independence.

The constant variance assumption was tested by plotting the observed residual values against the predicted direct labor hour values. This assumption was accepted if the residuals tended to randomly scatter around the mean (zero line) and if 95 percent of the residuals were within plus or minus two standard deviations of the mean (17:240).

Two methods were used to test the normality of the error term distribution. First, if about half of the residuals were positive and half were negative, the normality assumption was accepted (17:101).

The second, and more stringent test, was the Kolmogorov-Smirnov (K-S) test (17:112).

> The basis of the K-S estimation procedure is the cumulative sample function, . . . denoted by S(X). S(X) specifies for each X the proportion of values less than or equal to X. . . . The K-S procedure utilizes a statistic denoted by D(n), which is based on the differences between the cumulative probability function F(X). . . . D(n) equals the largest absolute deviation of S(X) from F(X) at any value X [2:29-30].

The K-S statistic used in this research was calculated by the Statistical Package for Social Sciences (SPSS). The data distribution was considered normal if the calculated statistic was below the critical value in the K-S one-sample test tables at the 5 percent level (16:51).

The Durbin-Watson test was used to check for autocorrelation of the residuals. The correlation of the residuals with past values is called autocorrelation (14:444). The null and alternate hypotheses were:

H_0: $p > 0$,

H_A: $p = 0$;

where p = the parameter of autocorrelation. The null hypothesis was accepted if the Durbin-Watson statistic (D), obtained from SPSS, was less than the upper bound; the alternative was accepted if D was greater than the lower bound. The results were inconclusive if D was between the upper and lower bound. The upper and lower bounds were obtained from Neave's Statistical Tables at the 0.05 significance level (16:62-63). If H_A was accepted, this supports the assumption of residual independence (17:358).

While the residuals were tested for autocorrelation, the presence of autocorrelation would not necessarily lead to rejection of the model. Smith cautioned against rejecting the model for autocorrelation.

> This check for autocorrelation may be somewhat distorted in regression analysis of unadjusted labor requirements for airframe manufacture. Peaks in the unit data caused by major engineering or model changes show up as runs of positive and negative residuals. Since these are symptoms similar to that of autocorrelation, one may be misled into rejecting a model when it does not exist. Therefore, in testing for autocorrelation, care is taken to account for alternative sources of runs in the residuals [19:51-52].

If autocorrelation were found to be present in the residuals, the data were examined for the changes which could cause a false indication of autocorrelation. If these peaks in the data were present, the test for autocorrelation would be inconclusive. If autocorrelation was found to be absent or inconclusive in the residuals, the model appropriateness test was subsequently performed.

Model Appropriateness Test. The multiple coefficient of determination (R^2) was the criterion test used to measure the appropriateness of the model. The R^2 value is an indication of how well the model fits the set of observed data. R^2 represents the fractional reduction in sample variation of the logarithm of the direct labor hours variable that is attributable to the full model. The R^2 value was obtained from the output of the SPSS program used in this research.

Smith used a value called R^2 actual. "This transformation to logarithms somewhat obscures the interpretation of R^2 with respect to the true variable of interest, hours per pound [19:53]." Smith's variable of interest, hours per pound, corresponds to the authors' research project variable of interest, direct labor hours. Smith's R^2 actual reduced the effect of transformation of the variables (19:53).

> Termed R^2 actual, a calculation analogous to that for R^2 is performed on the variables expressed in their original form. Specifically, a SSTO[6] actual is calculated by summing the square of the difference between each observed value of hours per pound and their mean. Each observation is predicted by the model in logarithms and then transformed to the original form. Actual residuals are then calculated, squared and summed producing an SSE actual. The R^2 actual statistic is calculated by dividing SSE actual by SSTO actual and subtracting the quotient from one [19:53].

Both R^2 and R^2 actual were used for this test. An appropriate model would explain a high proportion of variation in direct labor hours, and would consequently produce a high R^2 (6:37). Therefore, an R^2 value, both R^2 and R^2 actual, of 0.75 or lower was selected as the level at which the model would be inappropriate (2:31).

If all four of the foregoing research tests were not rejected, the full model would be accepted as suitable for fitting the data. Thus, production rate would be identified as an important explainer of variation in direct labor hour requirements in A-10 airframe production. However, if any one of the four tests were rejected, Research Hypothesis One was rejected. In that case, it would make little sense to test Research Hypothesis Two because the

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[6]Sum of squares total (SSTO) represents the sum of the sum of squares regression (SSR) and the sum of squares error (SSE).

full model would not fit the data better than the reduced model and no further tests would be done. However, if the model was not rejected using Research Hypothesis One testing, then the predictive ability would be tested under Research Hypothesis Two.

Research Hypothesis Two

Research Hypothesis Two stated that the full model is a better predictor of direct labor requirements than the reduced model. Both a statistical significance test and criterion test were used to evaluate this hypothesis. The two tests for evaluating Research Hypothesis Two were as follows:

1. Average absolute deviation test (statistical test), and
2. Percentage deviation test (criterion test).

Smith simulated future predictive ability of the observed data. He described this process as follows:

> To simulate this situation, the regression coefficients in the model are estimated with the last few observed data points omitted. Then using the new model, omitted values (which are known but not used in estimating the model coefficients) are predicted. Comparisons are then drawn between the actual and predicted hours as a subjective measure of predictive ability [19:56].

The approach was also used in this research project. The statistical test was used to determine if the full model predictions were significantly better than the reduced model predictions. If the full model was found to be a statistically significantly better predictor, a criterion test was applied to establish whether the predictions were accurate enough to be used for contract cost negotiation.

Average Absolute Deviation Test. This statistical test was performed to determine if the average absolute deviation of the full model was significantly less than that of the reduced model. The average absolute deviation of the full and reduced model are annotated by $|\bar{D}_F|$ and $|\bar{D}_R|$, respectively. The average absolute deviation was calculated by summing the absolute value of the differences between the actual and predicted direct labor hours for each data point, and dividing by the number of data points (n) (2:33). The null and alternative hypotheses were:

$$H_0: \quad |\bar{D}_R| \leq |\bar{D}_F|;$$
$$H_A: \quad |\bar{D}_R| > |\bar{D}_F|.$$

The null and alternate hypotheses were then tested using the Student's t distribution for less than sixty test situations. Research Hypothesis One assumptions of normality and randomness were also applicable to the average absolute deviation test. The t-test decision rules are summarized in Table 7.

TABLE 7

DECISION RULES (2:34; 19:41)

Reject H_0 if $t > t_{\text{table value}}$

at a significance level of 0.05

where:

$$t = (|\bar{D}_R| - |\bar{D}_F|) \,/\, \sqrt{(S_R^2/N) + (S_F^2/N)}$$

and

S_R^2 = variance of the distribution of deviations obtained with the reduced model,

S_F^2 = variance of the distribution of deviations obtained with the full model, and

N = the number of test situations.

The average absolute deviation test was used to determine whether the full model was a better predictor of direct labor hours than the reduced model. However, the average absolute deviation test does not tell how much better or how accurate the predictions were. Therefore, the percentage deviation test was developed to determine how much better and how much more accurate the full model was versus the reduced model. The percentage deviation test was performed next if the full model was found to be a better predictor than the reduced model.

Percentage Deviation Test. In order to use the full model for predictive purposes, some estimate of how much better a predictor the full model is over the reduced model is needed. By concluding that the full model predicts the required direct labor hours within a 5 percent accuracy, this research would be more meaningful to the users. For this reason, the percentage deviation test was used in this project. In performing the percentage deviation test, the individual deviations for each model were converted into a deviation measure expressed as a percentage of actual direct labor hours. The percentage deviations were calculated by subtracting the predicted direct labor hours from the actual direct labor hours and dividing by the actual direct labor hours. Next, the quotient was multiplied by 100 to form a percentage. This calculation was performed for each data point for both the full and reduced models. The percentage deviation measure was used to compare the results between the full and reduced models. Two categories were then selected for the deviations.

A deviation percentage between 5 and 10 percent constituted a good predictive ability of a model and a percentage less than 5 percent was categorized as excellent (2:35). The number of good and excellent test situations were then separately summed for the full and reduced models. The model with the largest number of good and excellent ratings was then selected as having the best predictive capability. The largest number of excellent ratings was used as a tie breaker if required. Although this was a simple, subjective test, it permitted a comparison of the accuracy of each model in predicting future direct labor hour requirements.

Data Collection and Treatment

Data Collection

Because this research replicated Smith's full model and extended the application of Smith's model to production data on a modern aircraft program, accessibility was the primary factor in selecting data. The A-10 program was selected and historical data from the established ongoing A-10 aircraft production program were collected. The A-10 data set contained fifty-one data points. Thirty-nine of the data points were used to obtain the regression model coefficients. The last twelve data points were used to test the predictive ability of Smith's model.

The A-10 historical data were provided directly by the prime contractor in the following format:

1. number of aircraft delivered each calendar month,

2. actual aircraft direct labor hours by tail number, and

3. cumulative number of aircraft produced.

Treatment of the data was necessary to tailor the data to the model as discussed in the following section.

Direct Labor Hours Treatment

Data for direct labor hours were provided by the prime contractor for the A-10 program in six general categories. The categories were as follows:

1. Farmingdale assembly,
2. Farmingdale pylon assembly,
3. Hagerstown bonding,
4. Hagerstown basic and subassembly,
5. Hagerstown final assembly, and
6. Hagerstown hangar chase aircraft and painting.

The average direct labor hours per aircraft per month was obtained by summing the six categories for each month and dividing this summation by the number of aircraft delivered during the month. Partially completed aircraft were excluded from the calculations because the prime contractor was unable to provide the start and completion dates for each aircraft. For this research, a calendar month was used which had a varying number of work days available due to weekends and holidays. The effects of this variation upon the results of this research could not be determined.

In addition, the hangar chase aircraft and painting category of work included direct labor hours expended on the chase aircraft maintenance rather than the A-10 aircraft in production. However, the direct labor hours associated with the chase aircraft maintenance were assessed to be relatively constant and to have minimal impact upon the research results.

Cumulative Output Treatment

The A-10 data used in this research project covered the period from September 1977 through November 1981. This data collection period included aircraft number 59 through 573. A-10 data were not available for aircraft produced prior to September 1977 and after November 1981. The value for the cumulative output variable was the number of the last aircraft delivered in a calendar month. For example, four aircraft were delivered in the month of September 1977 starting with aircraft number 59 and ending with aircraft number 62. Therefore, the first value for cumulative output was 62.

Production Rate Treatment

The prime contractor provided the researchers with a delivery schedule which included the actual monthly delivery rates. Since the actual production rate in the factory was not available to the researchers, the delivery rate was used as a proxy for the actual A-10 production rate.

The use of monthly delivery rate as a proxy for the monthly production rate has been utilized in other research efforts (5; 19). Smith compared the use of manufacturing rate versus delivery rate as a proxy for production rate. Smith found that the differences were so small between the two rates that there was insufficient evidence to conclude that one rate was clearly better than the other rate (19:80,132,144).

Congleton and Kinton, in their validation of Smith's research, compared the delivery rate versus the manufacturing rate as a proxy for the production rate. Congleton and Kinton found no significant difference between the two rates (5:62,75).

As Allen and Farr pointed out, caution must be exercised when proxies are used for the production rate, since the delivery rate to an operational wing may bear little or no resemblance to the actual production rate at the plant (2:22). Allen and Farr's caution was considered in this research project. However, based upon Smith's findings, Congleton and Kinton's findings, and the assumption that the time from the completion of the aircraft until delivery was relatively constant, the monthly A-10 delivery rate was considered as a suitable proxy for the monthly A-10 production rate for this research project.

The production rate varied from a low of four aircraft per month to a high of thirteen aircraft per month.

However, one third of the thirty-nine data points used to determine the regression coefficients as well as the twelve data points used for prediction had a delivery rate of twelve aircraft per month.

The data collection and treatment has been described. Summary lists of assumptions and limitations for this research project follow.

Assumptions and Limitations

Summary List of Assumptions

1. The historical data collected from the prime contractor were recorded accurately.

2. Multicollinearity did not impair the short-range predictive ability of the model.

3. The data points used in the data analysis were determined accurately from the prime contractor's source data.

4. Logarithmic transformations of the data to facilitate multiple linear regression analysis introduced no significant loss of data precision.

Summary List of Limitations

1. A limited number of data points (i.e., thirty-nine) resulted in a reduction of statistical "leverage" (i.e., limited degrees of freedom).

2. The predictive ability of the models will be adversely affected by exceeding the data range used in obtaining the model coefficients.

3. The applicability of the research results was constrained to the particular program from which the observations were used to construct the data base.

Summary

Two research hypotheses were established for this research project, and statistical and criteria tests were utilized to evaluate the two research hypotheses. The first hypothesis stated that the production rate variable explains a significant amount of additional variation in direct labor hour requirements for A-10 aircraft production. This first research hypothesis was tested by using a model utility test, a production rate variable value test, a model suitability test, and model appropriateness test. The second research hypothesis stated that the full model is a better predictor of direct labor hour requirements than the reduced model. The second research hypothesis was tested by employing two tests: the average absolute deviation test and the percentage deviation test. The acceptance of the two research hypotheses would establish the value of including the production rate variable as a factor for establishing A-10 aircraft cost.

Historical data were obtained from the prime contractor's established, ongoing A-10 aircraft production program. The three variables used in the two regression models were obtained from this data. The three variables were direct labor hours, cumulative output, and delivery rate. The use of the delivery rate as a proxy for the production rate was assumed to be an acceptable approach for this research project.

The two regression models, the basic learning curve model, and Smith's model were defined. Summary lists of assumptions and limitations for this research project were then presented. The assumptions addressed data accuracy, effects of multicollinearity on the predictive ability of the models, and logarithmic transformations of the data. The limitations included the limited statistical leverage due to the small number of data points, the effects of exceeding the data range on the predictive ability of the model, and the applicability of this research effort to other aircraft programs.

In the next chapter the performance of the methodology established in this chapter to test the two hypotheses is discussed. The data are analyzed, and the SPSS program used to obtain the regression coefficients is described.

CHAPTER IV

DATA ANALYSIS AND FINDINGS

Introduction

In Chapter III the two research hypotheses were stated, and a research methodology for testing the two hypotheses was described. This chapter presents an analysis of the A-10 attack data and tests the two research hypotheses using Chapter III's methodology. This chapter is divided into four major sections as follows:

1. Data Description and Analysis
2. Program Description and Output
3. Research Hypotheses Analysis
4. Summary

Data Description and Analysis

Data Description

As stated in Chapter III, the data were obtained directly from Fairchild Republic Industries in the following format:

1. number of aircraft delivered per calendar month,
2. actual aircraft direct labor hours by tail number, and
3. cumulative number of aircraft produced.

The data set included fifty-one data points, beginning with September 1977 and extending through November 1981. The raw data were treated as described in Chapter III. The data were transformed into logarithms with the first thirty-nine data points used to obtain the multiple linear regression coefficients and parameters. The final twelve data points were used to evaluate the predictive ability of the models. Prior to placing the data into the multiple linear regression program, the data were analyzed to determine the characteristics expected of representative learning curve data.

Data Analysis

Previous empirical research did not examine the data prior to program input. However, an analysis of the data prior to program input can provide the researcher with insight into probable outcomes or possible problem areas. For example, if a learning curve type of relationship is expected, but upon examination the number of direct labor hours increases as subsequent units are produced, this would indicate to the researcher that the wrong model for the data may have been chosen. The data obtained from the A-10 attack aircraft production program were examined for learning curve conformance and inconsistencies.

It was difficult to evaluate the raw data for learning curve conformance. However, a scattergram of the data permitted an accurate evaluation of the data. When the number of direct labor hours used was graphed versus the cumulative output, the result was a graph that started with a high value which was reduced quickly as the graph moved from left to right, and flattened out toward the right end, which was consistent with learning curve theory. A scattergram was made with the direct labor hours scaled on the ordinate (Y axis) and the cumulative output on the abscissa (X axis). Figure 1 provides the scattergram. Due to the proprietary nature of the direct labor hours data, the actual A-10 values have been masked. Figure 1 shows that the scattergram has the shape expected of a learning curve. Often learning curve data is graphed on log-log paper which shows the learning curve as a straight line with a negative slope.

Since the computer output did not have a log-log scale, the A-10 data were transformed and a second scattergram was produced. The transformation of the data had the same effect of graphing the untransformed data on log-log paper. Therefore, a straight line was expected. Figure 2 is a scattergram of the logarithms of direct labor hours and cumulative output. Again, the direct labor hours were masked to protect the proprietary nature of the data. The Figure 2 scattergram supported the concept that the

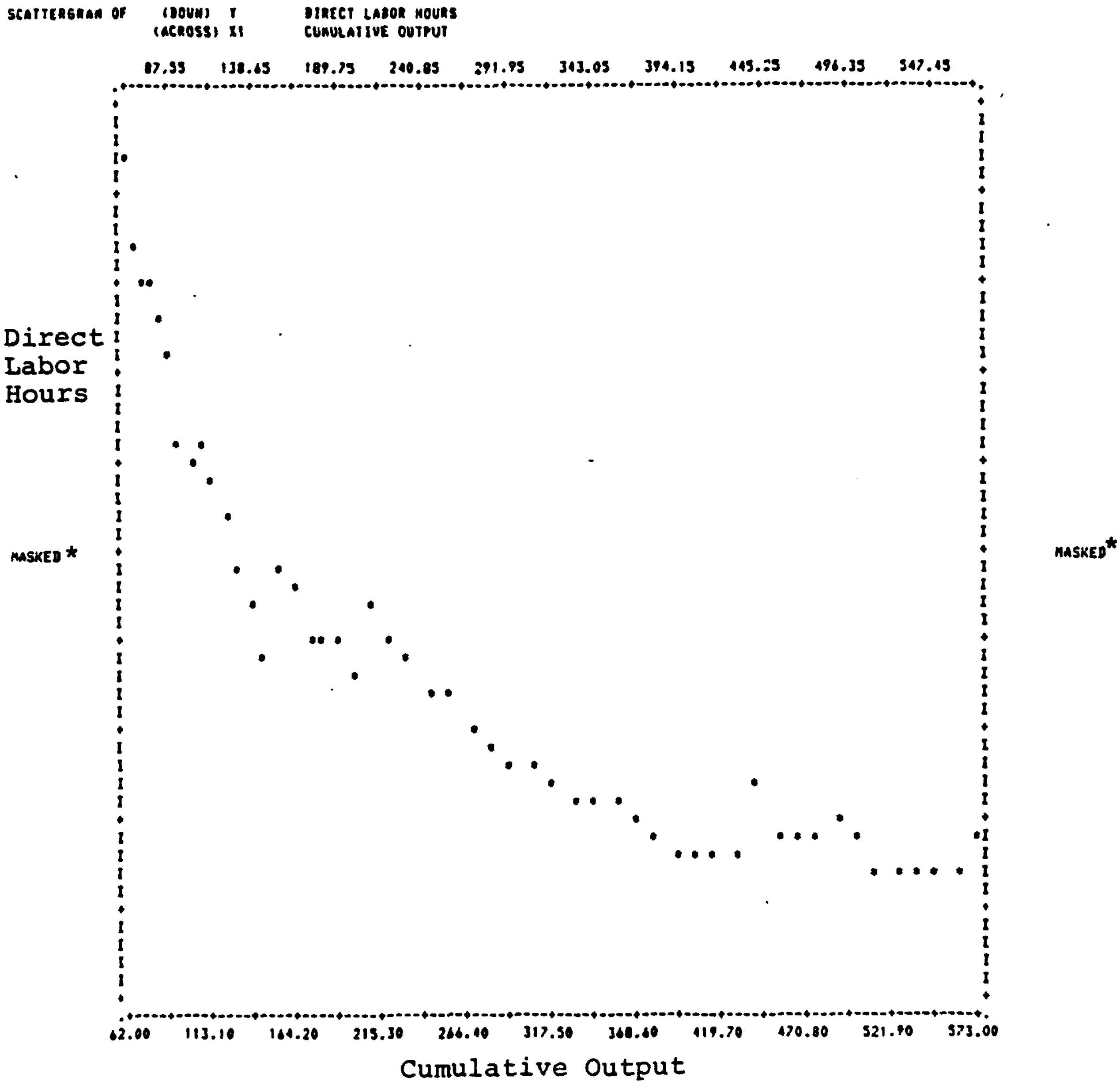


Fig. 1. Scattergram of Direct Labor Hours versus Cumulative Output

*These data are proprietary and cannot be released without written permission from the prime contractor.

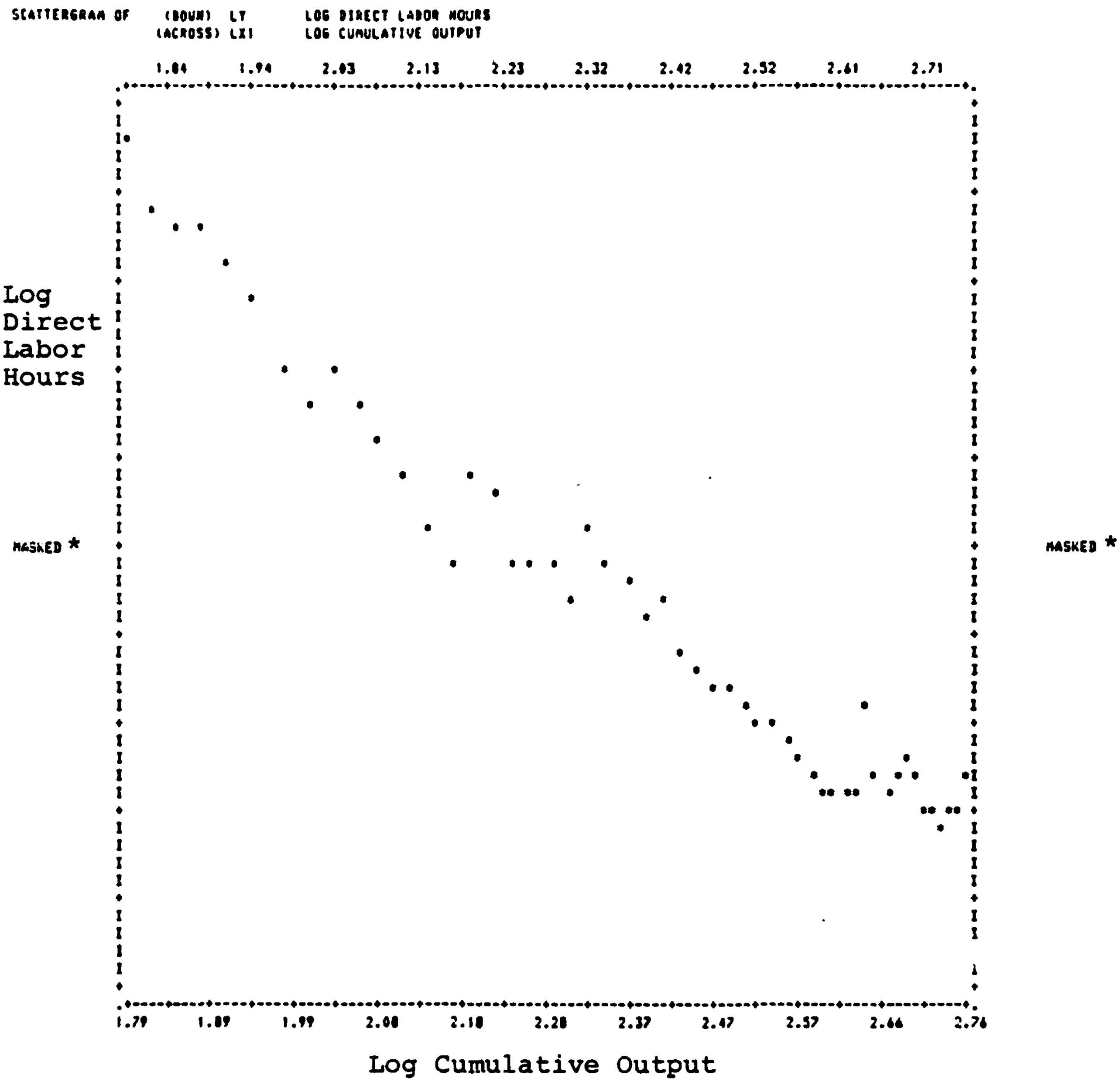


Fig. 2. Scattergram of Log Direct Labor Hours versus Log Cumulative Output

*These data are proprietary and cannot be released without written permission from the prime contractor.

data fit a learning curve. However, each scattergram (Figures 1 and 2) showed areas which deviated from the learning curve relationship. These apparent inconsistencies in the data set are discussed below.

These inconsistencies in the scattergrams appear as a sudden increase in direct labor hours. There are seven peaks that show this sudden increase. These inconsistencies occur at the following points: (1) 108/2.03 (actual/logarithm), (2) 155/2.19, (3) 211/2.32, (4) 257/2.41, (5) 441/2.64, (6) 489/2.69, and (7) 573/2.76. These variations probably caused a small decrease in the ability of the model to fit the data. The greatest potential impact was in the predictive ability of the models because three of the seven deviations occur within the last twelve data points which were used to evaluate the predictive ability of the models. In addition, as Smith noted, peaks in the data occur as runs of positive and negative residuals which may give a false indication of autocorrelation (19:51).

The analysis of the A-10 data indicated that the data set represents a learning curve relationship and that a good fit of the data to our models was expected. Because the seven peaks in the data could lessen the fit of the data to the models or provide a false indication of autocorrelation, these inconsistencies in the data were considered when testing the models. In testing the models, the first step was to compute parameters. The program used to obtain these parameters and their values are discussed below.

Program Description and Output

Program Description

The computer program used in this research project to obtain the coefficients (B_0, B_1, and B_2) and parameters for the full and reduced models was written in the Statistical Package for the Social Sciences (SPSS) programming language. Although the PRODRATE program written by Allen and Farr (2) was filed under the Copper-Impact System, access to Allen and Farr's program was not available due to research budget constraints. The use of the SPSS package did not degrade the accuracy of the regression coefficients or parameters.

Data Input. The program read the input data in the following order: direct labor hours, cumulative output, and delivery rate. These three values constituted a data point or case. For this research fifty-one cases were utilized. After the data was read by the computer, the data were converted to logarithms.

Data Transformation. The data were transformed to logarithms by using the compute command in SPSS. These transformed cases were the values used to obtain the regression coefficients and parameters.

Regression Command. The SPSS program, through the regression command, calculated the regression coefficients and parameters. By assigning a case weight of one to the first thirty-nine cases and a case weight of zero to the last twelve cases, the regression command used the first thirty-nine cases to calculate the regression coefficients and parameters, and then predicted the final twelve values for the logarithm of the direct labor hours using the calculated model regression coefficients. The program computed the residual (error) for each of the fifty-one cases. The values obtained for the regression model coefficients and parameters were program output which are discussed in the next section.

Program Output

The output from the SPSS program was used to test the two research hypotheses. One of the first outputs generated by the SPSS program was the correlation values, which are equal to the R^2 values when each listed variable was regressed with the other listed variables. This output indicated the extent of multicollinearity which existed between the two independent variables. The next set of values outputed was for the regression model. The values were as follows:

1. R^2,

2. Sum of Squares Regression (SSR),

3. Sum of Squares Error (SSE),

4. Mean Sum of Squares Regression (MSR),

5. Mean Sum of Squares Error (MSE),

6. F, and

7. Significance of F.

These seven values were used to test Research Hypothesis One. The model coefficients were obtained along with the 95 percent confidence interval for each coefficient. If zero was included within the confidence interval, the hypothesis that the coefficient was equal to zero could not be rejected.

The final output values were the following:

1. Logarithm of the direct labor hours,

2. Estimated logarithm of the direct labor hours from the model,

3. Predicted logarithm of the direct labor hours,

4. Residual plot, and

5. Durbin-Watson statistic.

The analysis of the research hypothesis using the SPSS output values is discussed below.

Research Hypotheses Analysis

This section reviews the research hypotheses and the methodology for testing them. The outputs of the SPSS program and the performance of the two hypotheses tests are discussed. Finally, the results of the tests are summarized.

Research Hypotheses and Methodology Review

For ease of reference, the statistical and criterion tests for each of the research hypotheses are summarized and restated below:

Research Hypothesis One. The production rate variable explains a statistically significant amount of the variation in direct labor requirements for A-10 aircraft production. Tests used for this hypothesis were:

1. Model Utility Statistical Test.

   H_0: $B_1 = B_2 = 0$;

   H_A: At least one coefficient is nonzero.

   Decision Rule: Reject H_0 if calculated F-ratio is greater than F-critical.

2. Production Rate Variable Value Statistical Test.

   H_0: $B_2 = 0$;

   H_A: $B_2 \neq 0$.

   Decision Rule: Reject H_0 if calculated F-ratio is greater than F-critical.

3. <u>Model Suitability Criterion Test</u>. The model was not rejected as inappropriate if the observed residuals displayed the same properties (constant variance, normal distribution, independence) as the random error term.

4. <u>Model Appropriateness Criterion Test</u>. If the model's computed R^2 and actual R^2 exceeded .75, the model was accepted as appropriate.

<u>Research Hypothesis Two</u>. The full model is a better predictor of direct labor requirements than the reduced model. Hypothesis Two was tested using:

1. <u>Average Absolute Deviation Statistical Test</u>.

H_0: $|\bar{D}_R| \leq |\bar{D}_F|$;

H_A: $|\bar{D}_R| > |\bar{D}_F|$.

Decision Rule: Reject H_0 if t-calculated is greater than the t-critical value (.05).

2. <u>Percentage Deviation Criterion Test</u>. The model with the largest number of good (within ±10 percent accuracy) and excellent (within ±5 percent accuracy) ratings was selected as having the best predictive capability. The highest number of excellent ratings was used as a tie breaker if necessary.

SPSS Program Output Results

The output obtained from the SPSS prog .m used in this research project is contained in Table 8.

TABLE 8

SPSS PROGRAM OUTPUT RESULTS

Item	Reduced Model	Full Model
Estimated B_0	*	*
Estimated B_1	-0.24074896	-0.22170676
Estimated B_2	N/A	-0.03391380
95% C.I. for B_0	*	*
95% C.I. for B_1	-0.25527091 to -0.22622702	-0.27176144 to -0.17165209
95% C.I. for B_2	N/A	-0.11918123 to 0.05135362
R^2	0.96825	0.96881
SSR	0.14349	0.14357
SSE	0.00471	0.00462
MSR	0.14349	0.07179
MSE	0.00013	0.00013
F/Significance	1128.34212/0	559.16991/0.000
Durbin-Watson	0.82675	0.85595

*This data is proprietary and cannot be released without written permission from the prime contractor.

The predicted values obtained from the full and reduced models were plotted versus logarithm cumulative output as shown in Figures 3 and 4.

Research Hypothesis Test Results

Research Hypothesis One Test Results. A summary of the results of the two statistical tests is shown in Table 9. A more complete discussion of each test follows.

1. Model Utility Statistical Test Results. The null and alternate hypotheses were as follows:

H_0: $B_1 = B_2 = 0$;

H_A: At least one coefficient is nonzero.

Decision Rule: Reject H_0 if the calculated F-ratio is greater than F-critical.

The two F values are as follows:

Calculated F-ratio = 559.16991;

F-critical (α=0.05, d.f. 1,36) = 4.17 (14:638).

Since the calculated F-ratio is clearly greater than F-critical, the null hypothesis was rejected. This means there is a significant relationship between the logarithm of direct labor hours and the independent variables, logarithm of cumulative output and logarithm of delivery rate. The test results indicate that at least one of the independent variables was a significant explainer of variation in direct labor hours. The next test evaluated the

SCATTERGRAM OF (DOWN) LYHAT1 EST LOG DIRECT LABOR HOURS REDUCED
(ACROSS) LX1 LOG CUMULATIVE OUTPUT *

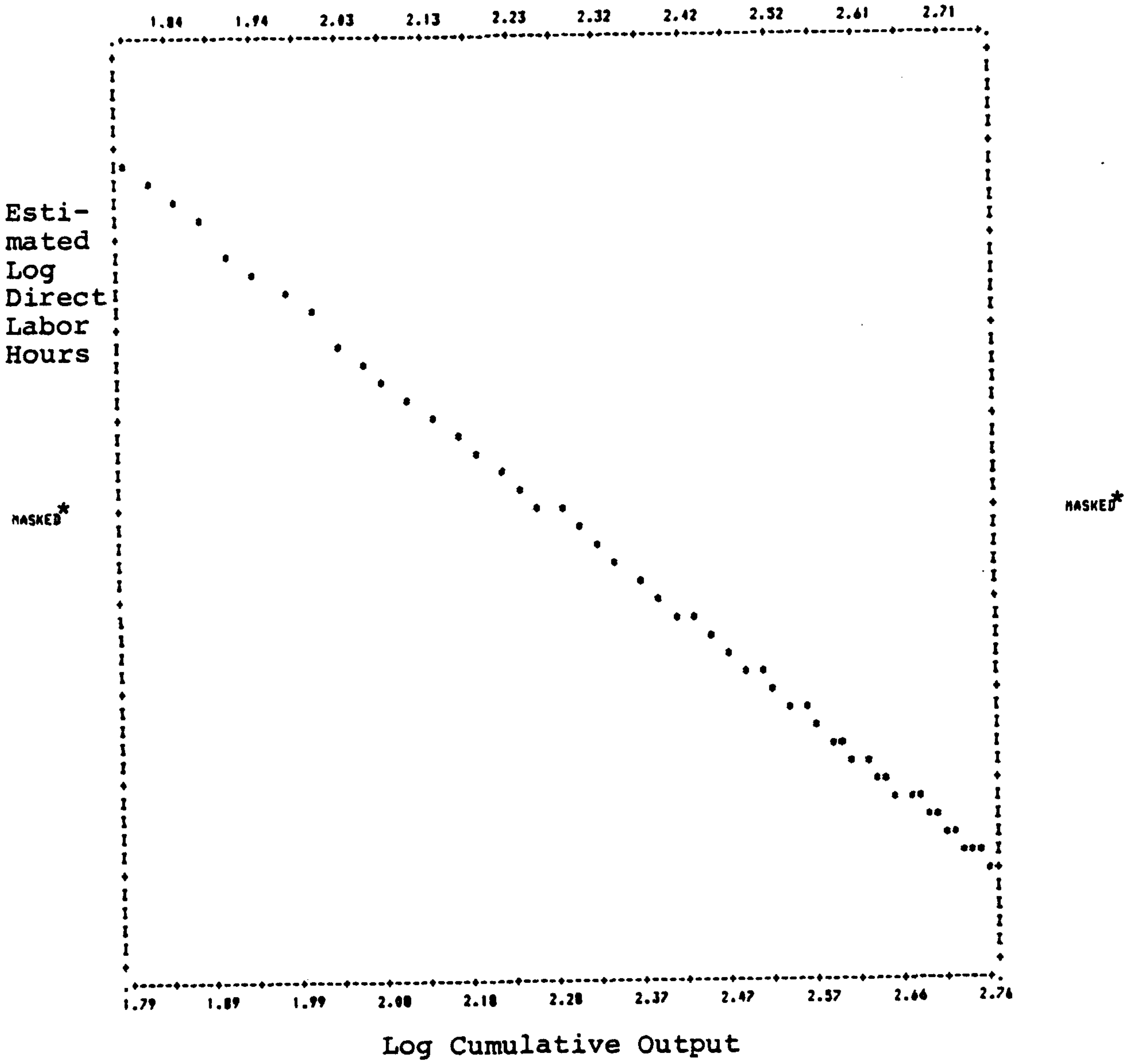


Fig. 3. Scattergram of the Reduced Model

*These data are proprietary and cannot be released without written permission from the prime contractor.

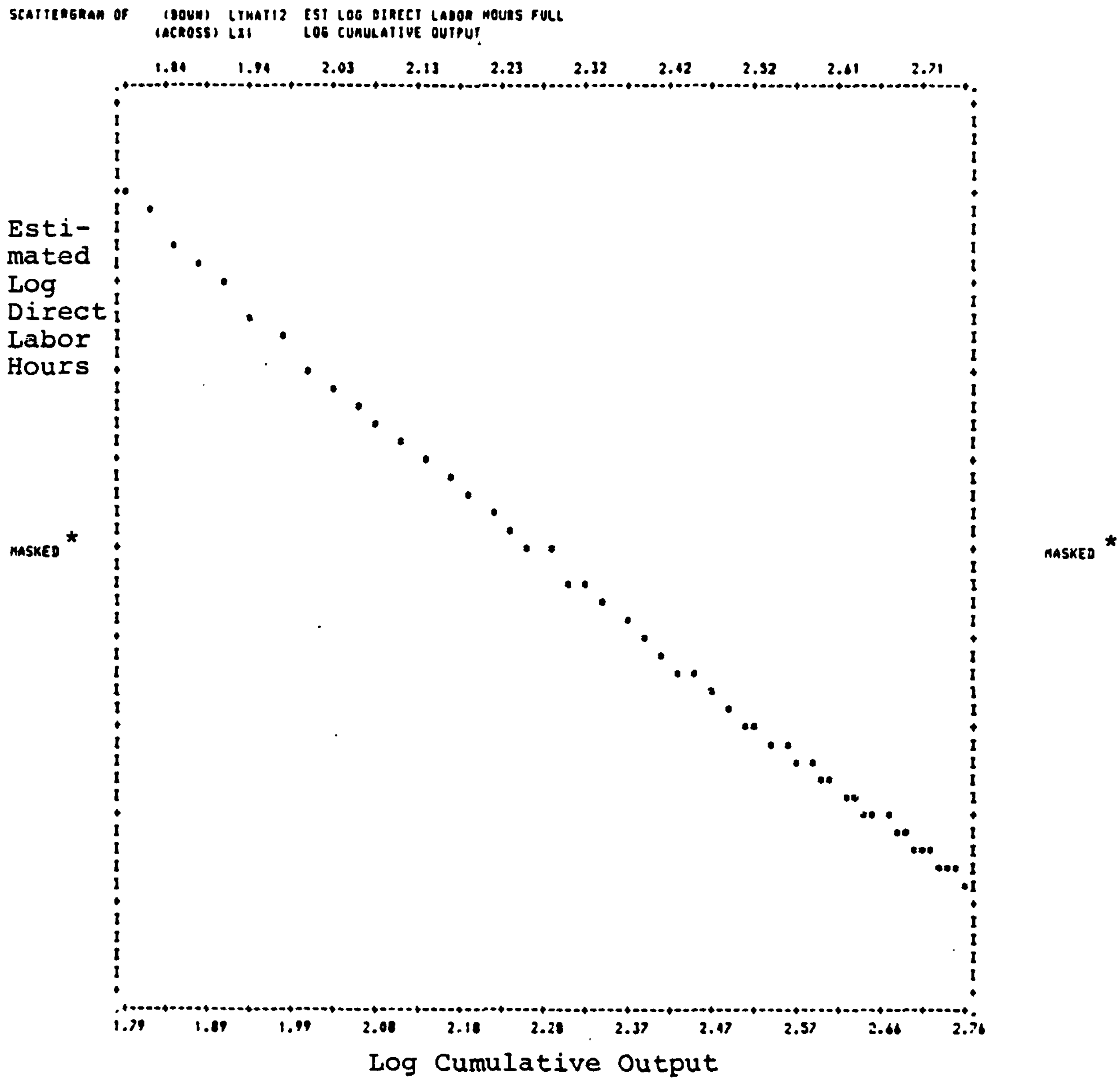


Fig. 4. Scattergram of the Full Model

*These data are proprietary and cannot be released without permission from the prime contractor.

TABLE 9

RESEARCH HYPOTHESIS ONE TEST RESULTS

Test	Items	Reduced Model	Full Model
<u>Model Utility</u>			
	F-ratio	1128.34212	559.16991
	F-critical	N/A	4.17
Decision			Reject H_0
<u>Production Rate Variable Value</u>			
	F-ratio	N/A	0.623
	F-critical	N/A	4.17
Decision			Fail to Reject H_0

delivery rate variable's role as a significant explainer in direct labor hour variation.

2. <u>Production Rate Variable Value Statistical Test Results</u>. This second test of the production rate variable was similar to the first statistical test except that it evaluated the hypothesis that B_2 equals zero. The null and alternate hypotheses are as follows:

H_0: $B_2 = 0$;

H_A: $B_2 \neq 0$.

Decision Rule: Reject H_0 if the calculated F-ratio is greater than F-critical.

The two F values are as follows:

Calculated F-ratio = 0.623;

F-critical (α=0.05, d.f. 1,36) = 4.17 (14:638).

Since the calculated F-ratio is less than F-critical, the decision was to fail to reject H_0. Therefore, the logarithm of the delivery rate variable was not a significant explainer of variation in the logarithm of direct labor hours, and Research Hypothesis One was rejected.

As discussed in Chapter III, multicollinearity can effect the results of the foregoing statistical test. The correlation coefficient for the relationship between the two independent variables was 0.95649. This correlation coefficient means that the independent variables are highly correlated (i.e., as one increases in value the other increases). The total sum of squares is a constant for this data since the total sum is equal to the sum of the sum of squares regression (SSR) and the sum of squares error (SSE). To evaluate the logarithm of the delivery rate variable as an explainer of the logarithm of the direct labor hour variation, the model using the logarithm of the delivery rate alone was evaluated using the SPSS program.

The results of the regression of the delivery rate alone model showed an R^2 equal to 0.89891 and an F-ratio equal to 329.00283. These values show that the model is valid at the 0.05 level since the calculated F-ratio is greater than F-critical.

For all model data the total sum of squares (SSTO) is equal to 0.1482. The logarithm of the cumulative output variable explains 0.14349 of the SSTO for the reduced model. The logarithm of the delivery rate, when evaluated separately from the cumulative output, explains 0.13321 of the SSTO. Together the two variables explain 0.14357 (SSR for the full regression model, Table 8). As discussed in Chapter III, when there is a high correlation between the independent variables, the sum of squares regression cannot be ascribed to an independent variable (17:253). Thus, although in the full model the delivery rate variable is credited with only explaining .00008 more variation than the reduced model's cumulative output variable, part of the remaining variation is jointly attributable to both of the independent variables. This same problem was noted in Smith's (19) previous research effort. Smith concluded that although the independent variables appeared to be correlated, the cumulative output variable increased even when the production rate decreased as long as the production rate was greater than zero (19:46). Therefore, the correlation between the independent variables did not follow the concept of multicollinearity. The above conclusions also applied to the A-10 data. The test would be considered valid even if multicollinearity was present because the purpose of this test was to demonstrate with statistical significance that the delivery rate variable explained a significant amount of additional variation in direct labor hours.

<u>Summary of Research Hypothesis One Test Results</u>. The full model was found not to be significantly better than the reduced model. Figure 5 depicts this graphically. As can be seen, the full model regression line is relatively parallel to the reduced model regression line, and the distance between the lines is small which confirms that the full model was not significantly better than the reduced model.

Because the null hypothesis in this test was not rejected, the Research Hypothesis One was rejected. Therefore, the production rate variable does not explain a statistically significant amount of additional variation in direct labor hour requirements for A-10 aircraft production.

<u>Research Hypothesis Two Test Results</u>. Because Research Hypothesis One was rejected, Research Hypothesis Two was not evaluated.

Summary

The data were analyzed based upon the methodology and data treatment described in Chapter III. The direct labor hour data were found to approximate a learning curve.

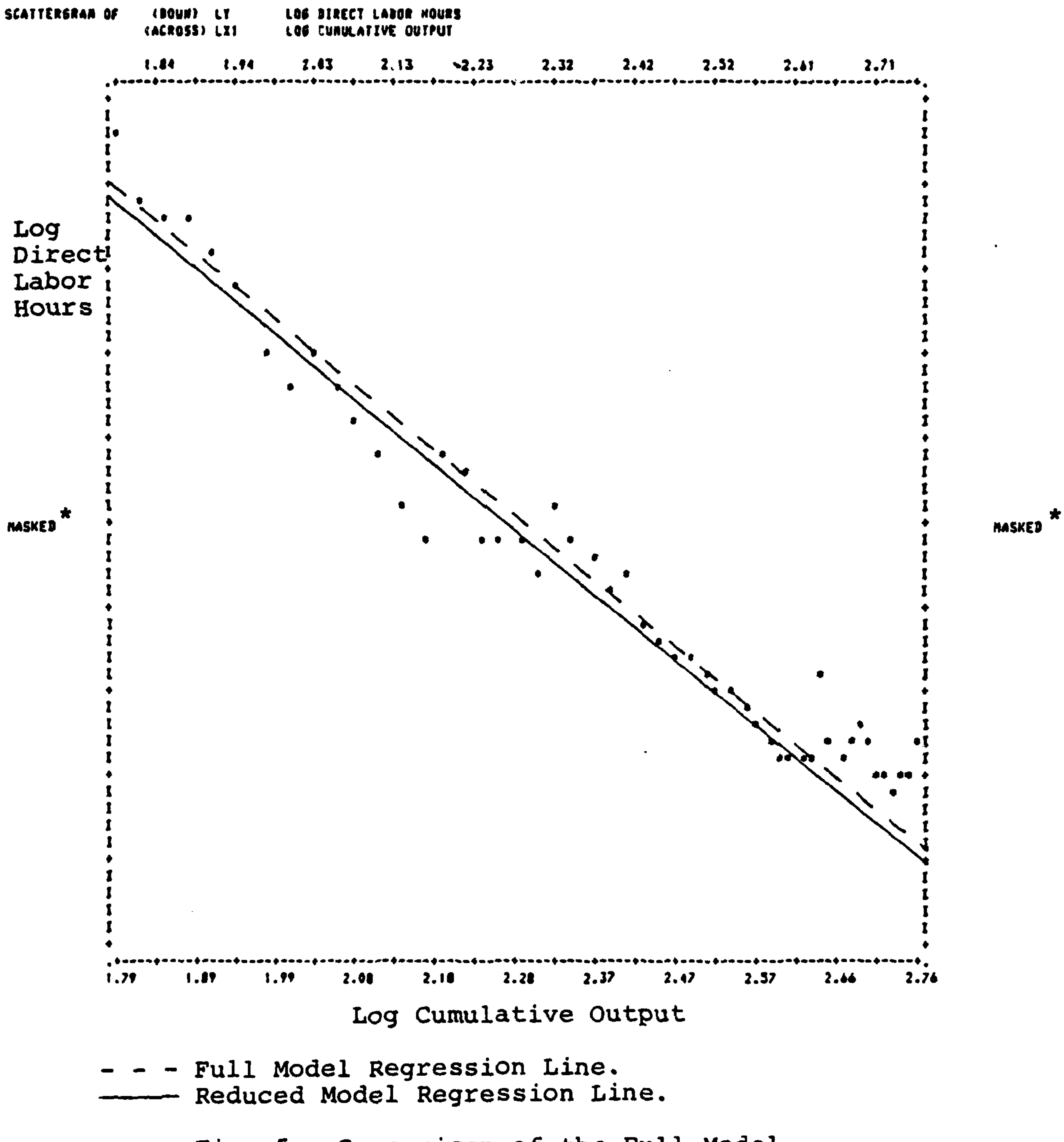


Fig. 5. Comparison of the Full Model to the Reduced Model

*These data are proprietary and cannot be released without written permission from the prime contractor.

However, there were unexplained peaks in the data which seemed to have no effect upon the results of this research. The SPSS program provided sufficient information to conduct a thorough data analysis. Research Hypothesis One passed the first statistical test of model utility. However, the second statistical test, Production Rate Variable Value test, caused the first research hypothesis to be rejected since the delivery rate variable, a proxy for production rate, did not explain a significant amount of additional variation in the full model.

Research Hypothesis Two was not evaluated because the first hypothesis was rejected.

Chapter V contains the summary, conclusions, and recommendations of this research.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Introduction

The results of the data analysis led to the conclusions and recommendations discussed below. This chapter is divided into four major sections as follows:

1. Summary of Previous Chapters
2. Conclusions
3. Recommendations
4. Summary

Summary of Previous Chapters

The Department of Defense is under ever-increasing pressure from Congress and the American public to provide national security at the lowest feasible cost. Providing national security through weapon system acquisition has become increasingly costly in the last decade. A significant determinant of weapon system cost is direct labor requirements (20:p.3-1). Direct labor costs are extensively estimated through the use of a learning curve model.

Learning curve models have been used extensively during the last thirty years to assist in cost estimating;

however, most models in use do not consider the effects of production rate variability on direct labor costs. Numerous studies (1; 2; 3; 4; 5; 6; 8; 11; 12; 17; 18; 19) have been conducted in an attempt to develop a more accurate direct labor prediction model which considered production rate variability. The majority of research studies in this area (1; 2; 4; 5; 6; 8; 17; 18; 19) concluded that production rate was a significant contributor to the predictive ability of the learning curve model. The basis for five such research efforts (2; 5; 6; 18; 19) was the full model developed by Lt Col Larry L. Smith.

Research Hypothesis One stated that the production rate explained a significant amount of additional variation in direct labor hour requirements for A-10 aircraft production. Two statistical and two criterion tests were used in the data analysis. The first statistical test was an F-test for model utility which determined if the dependent variable (labor hours) was related to the independent variables (cumulative output and production rate). The second test was an F-test which evaluated the additional value of including production rate to further explain direct labor hour variation.

The first criterion test analyzed the residuals for the assumptions of constant variance, independence, and normal distribution. The second criterion test analyzed the R^2 to determine the appropriateness of the model.

Conclusions

Smith's Production Rate Model should not be used by Air Force Contracting Officers to estimate future A-10 attack aircraft costs. Smith's Production Rate Model was not a more appropriate model than the basic learning curve model for estimating future A-10 direct labor hour requirements. The failure of the production rate variable to explain additional variation in direct labor hours was caused by the high correlation between the production rate and cumulative output variables. The two independent variables explained the same variation in direct labor hours due to multicollinearity. Because both variables must appear in Smith's model, the production rate variable was rejected as a significant explainer of direct labor hour variation. Therefore, Research Hypothesis One was rejected.

Another reason for the failure of the production rate variable to explain additional variation in direct labor hours may be in the nature of the learning curve. The number of direct labor hours required to produce an item is reduced by a constant percentage each time the number of units is doubled. For example, a 70 percent learning curve produces 1000 direct labor hours, for the first unit, 700 hours for the second unit and 490 hours for the fourth unit, etc. Thus, the learning curve model explained a large portion of the variation in direct labor hours. When a large number of units have been produced the learning curve approaches a horizontal line, and there is very little variation in direct labor hours between subsequent units. For example, using the same learning curve as in the first example, the number of direct labor hours required for the 1024th unit is 28.25, and the number of hours required for the 2048th unit is 20.25. This indicates little variation because the learning curve is becoming horizontal. If any variation is present at this point, it may be more easily explained by using Smith's production rate model.

The learning curve represented by the A-10 data in Figure 1 (see page 57) does not appear to be at the horizontal stage. Therefore, it was concluded that the variation in the direct labor hours resulted from learning or improvement that was taking place rather than variations in the production rate.

The success of Smith's research may have been due to the fact that the data was obtained from aircraft production programs where the learning curve was approaching a horizontal line (i.e., the flat portion of the learning curve). The type of production program which seems most appropriate for Smith's model is discussed below.

The ideal program for using Smith's Production Rate Model for estimating future direct labor requirements should have the following five characteristics. First, the program should be an established, ongoing program that has been producing units for at least forty-eight months. This is to allow for a minimum of thirty-six data points to obtain the regression coefficients and still maintain sufficient statistical validity.

Second, the program should either have a high learning factor, or produce a very large number of units per month. This will provide a learning curve that is near its horizontal stage.

Third, the data should be available and provide the following information:

1. Direct labor hours assigned to a unique unit and measured in hours or constant dollars,

2. Cumulative output providing the actual start and completion dates for each unit, and

3. Production rate by standardized accounting months.

Fourth, the production rate should vary by a large margin with increases and decreases in production rate occurring randomly. This is to reduce the chance of multicollinearity occurring between independent variables.

Finally, the user should have access to a computer which has a language available that can be used to obtain regression coefficients.

These conclusions are based solely upon this research effort. Further research in this area could provide additional insight into Smith's model and may explain why some programs fit the model while others fail. Recommendations for further research follow.

Recommendations

The success rate for the research using Smith's model in validating or replicating his model is approximately 60 percent. A listing of the success and failures of Smith's model is contained in Table 10. In this table, a success is defined as that circumstance where research hypotheses passed all tests contained in the methodology.

TABLE 10

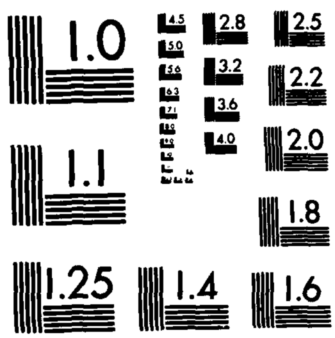
RESEARCH SUCCESS HISTORY

Researcher(s)	Number of Models	Number of Success	Percent Success
Smith	16	16	100
Congleton-Kinton	10	10	100
Stevens-Thomerson	10	2	20
Crozier-McGann	6	1	16.7
Allen-Farr	12	3	25
Bourgoine-Collins	1	0	0
Total	55	32	58.2

This low success rate has prevented Smith's model from being used extensively by Air Force Contracting Officers. Additional research is warranted to determine what characteristics cause the model to be a success or a failure as a predictor of direct labor hour requirements. Further, an easy test which determines if the production rate model is suitable for a given production program is needed. The data used in previous empirical research of the production rate model topic should be obtained and analyzed for properties that resulted in a success or properties that caused a failure. Additional study is also recommended in the A-10 program. A-10 production is forecasted to be reduced during fiscal years 1982, 1983, and 1984, thereby increasing variability of the delivery rate. With a more varied delivery rate, the multicollinearity present between the independent variables may be reduced. In addition, the learning will begin to approach its horizontal stage. Replication of this research methodology should be performed during fiscal years 1982 through 1984.

Summary

This research evaluated the use of the Production Rate Model developed by Larry L. Smith in the established, ongoing A-10 attack aircraft program for estimating future direct labor requirements. The hypothesis that the



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production rate variable was a statistically significant explainer of additional variation in direct labor hours for A-10 production was rejected. The production rate variable did not significantly explain more variation in direct labor than did the basic learning curve model. A high correlation coefficient value for the relationship between the independent variables was suggested as a possible reason for the lack of additional contribution by the production rate variable. Another conclusion was that because the data was obtained from the early stages of the learning curve, most of the variation in direct labor hours could be attributed to the learning curve and not to the production rate. Therefore, it was recommended that data from these previous studies be analyzed for common characteristics which might explain the reasons for success or failure of the production rate model.

Of the previous programs studied using Smith's model, approximately 60 percent supported the hypothesis that the inclusion of the production rate variable resulted in a better predictor.

APPENDIX

THE SPSS COMPUTER PROGRAM PRODUCTION RATE

```
RUN NAME        PRODUCTION RATE REGRESSION
VARIABLE LIST   Y,X1,X2
VAR LABEL       Y,DIRECT LABOR HOURS/
                X1,CUMULATIVE OUTPUT/
                X2,DELIVERY RATE/
INPUT FORMAT    FREEFIELD
INPUT MEDIUM    CARD
N OF CASES      51
COMPUTE         WEIGHT = 1.0
COMPUTE         LY = LG10 Y
COMPUTE         LX1 = LG10 X1
COMPUTE         LX2 = LG10 X2
VAR LABEL       LY,LOG DIRECT LABOR HOURS/
                LX1,LOG CUMULATIVE OUTPUT/
                LX2,LOG DELIVERY RATE/
IF              (SEQNUM GT 39) WEIGHT = 0.0
WEIGHT          WEIGHT
REGRESSION      VARIABLES=LY,LX1,LX2/
                REGRESSION = LY WITH LX1/
                RESIDUALS/
                REGRESSION = LY WITH LX1,LX2/
                RESIDUALS/
STATISTICS      ALL
READ INPUT DATA
FINISH
```

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BIOGRAPHICAL SKETCHES OF THE AUTHORS

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